C. Impact Modeling and Characterization of Spot Welds

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Objective

- Develop a new, robust spot-weld element (SWE) for modeling various modes of spot-weld failure as a function of impact, welding conditions and materials, while maintaining the current computational efficiency and ease-to-use.
- Develop the implementation procedure to incorporate SWE in crash-simulation FEA codes used by the automotive crash modelers.
- Generate a companion experimental database on the performance of advanced high-strength steel (AHSS) spot-weld behavior under various loading conditions and deformation rates to support and validate the modeling approach.

Approach

- A new SWE and associated constitutive models.
- Modeling and characterization of weld microstructure and property.
- Deformation and failure-behavior testing under different dynamic-loading conditions.

Accomplishments

- Finalized the plan for making weld coupons and dynamic testing.
- Completed literature review on modeling of spot welds.
- Initiated formulation of spot-weld element.

Future Direction

- Develop testing procedures for dynamic testing of spot-weld and produce preliminary data.
- Complete development of SWE to demonstrate its basic characteristics meeting the intended modeling requirements.

- Deliver initial version of the SWE and its implementation procedure.
- Demonstrate SWE-based model.

Introduction

This is a joint program between Oak Ridge National Laboratory (ORNL) and University of South Carolina (USC) sponsored by DOE FreedomCAR and USAMP. It aims at developing a novel and robust spot-weld modeling approach, supported by experimental data that can be implemented in crash simulation FEA codes used by the automotive crash modelers. ORNL's effort focuses on 1) a new, robust, spot-weld finite-element formulation and implementation procedure for modeling various modes of spot-weld failure as a function of impact, welding conditions and materials while maintaining the current computational efficiency; 2) validation of the new crash-modeling approach by component-level crash testing. The companion effort at USC is 1) to perform coupon-level dynamic testing to generate the experiment database of spot-weld performance under different loading modes and strain rates during impact, and 2) work with ORNL to formulate a failure criterion which can adequately deal with the failure-mode changes usually encountered during dynamic loading of spot-welds of high-performance and lightweighting materials such as advanced high-strength steels (AHSS) and aluminum (Al) alloys.

This program was approved in July 2006. Funding was provided to ORNL in August 2006. Therefore, very limited progress has been made in FY 2006. For this report, we will first describe the research needs, the planned technical approach, and the work scope of this research. We will then summarize the progress made in FY 2006.

A primary premise that drives increased use of AHSS in auto-body structures is the drastic improvement in crash performance while reducing the weight. Resistance spot-welding (RSW) is by far the most common joining process used in automotive manufacturing. Typically, there are thousands of spot-welds in a vehicle. Because the separation of spot-welds can affect the crash response of a welded structural component, the static and dynamic behavior of the spot-welds has been one of the critically important considerations in vehicle design and manufacturing.

RSW of AHSS presents unique technical challenges for automotive structure applications. Due to their high carbon and alloying element contents, AHSS are considerably more sensitive to the thermal cycle of welding than the conventional steels used in auto body structures. The higher-grade AHSS (e.g., DP800/1000, TRIP, boron) are more difficult to weld and more susceptible to forming brittle microstructures and solidification-induced defects in the weld region. In addition, heat-affected zone (HAZ) softening can occur. Therefore, RSW of AHSS can very exhibit different structural performance characteristics than the ones made of conventional steels [1-9]. For example, AHSS spot-welds can fail under different failure modes (button pullout, interfacial, or mixed). In addition, impact experiments on joints [7] and structural components (top-hat, double-hat sections) [8, 9] have shown that RSWs have different response under static and dynamic loads. Not only the behavior of RSW in AHSS can be different from that of conventional mild steels [9], the spot-weld structural performance among different AHSS can be drastically different and highly dependent on the grades and types of AHSS [2, 3] (see Figure 1. and Figure 2). Furthermore, there can be considerable variations in microstructure and properties in the weld region for a given type and grade AHSS made by different steel producers, due to the differences in steel chemistry and processing routes employed [5, 6].

In recent years, CAE-based simulation of dynamic (impact) behavior of auto-body structure during crash has become an indispensable tool that enables rapid and cost-effective design and engineering of crash-resistant auto-body structures. Currently, the behavior of spot-welds in FEM impact simulations is usually modeled with a kinematics representation of the joint and the associated constitutive model describing the material-related response of the joint [10]. Currently, the kinematics of the joint are treated as a point connection by means of flexible or

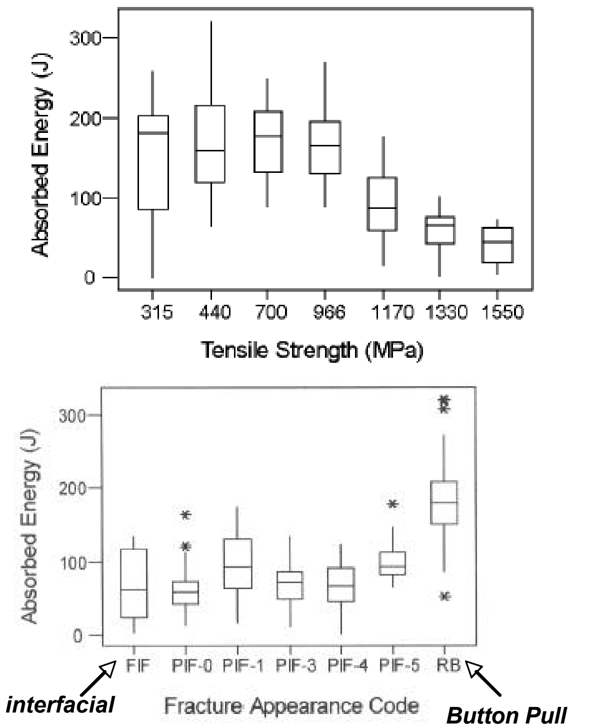

Figure 1. Impact energy in cross-tension test of resistance spot-welds made from different AHSS. After Peterson et al, 2000 [2].

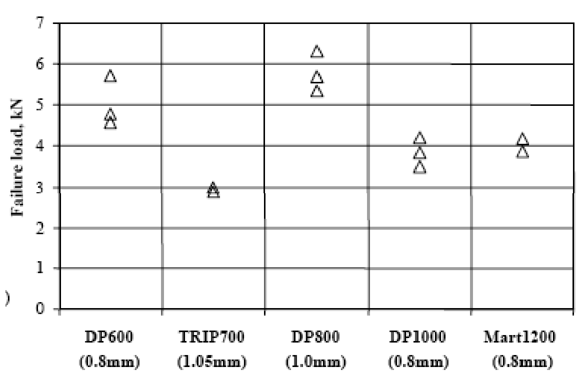

Figure 2. Static failure load in cross-tension test of resistance spot-welds made from different AHSS. After Shi et al, 2003 [3].

rigid (i.e., constrained) links. The sophistication of these beam-link models is limited and can practically involve only force-based laws. Deformation-based criteria require flexible beams or equivalently penalty-based formulations for which the material properties are difficult to assign.

The new constraint-based models [11] allow for independence of connecting FEM mesh topologies, but share similar limitations. The failure models can be derived from purely experimental data [12,13] or can be derived from assumed failure modes [14] fitted to experiments. One of the principal problems with beam-based kinematics models is that the stress and strain distributions in the weld area are not accurately represented. A simple illustration of this drawback is the distribution of through-thickness shear in the shear-lap joint model where nodes of two shells are joined via a beam. As shown in Figure 3, maximum shear stress is expected in reality. However, the shell element theory requires stresses to vanish on the shell surface and, therefore, the resulting stress/strain distributions in the weld area are not accurate.

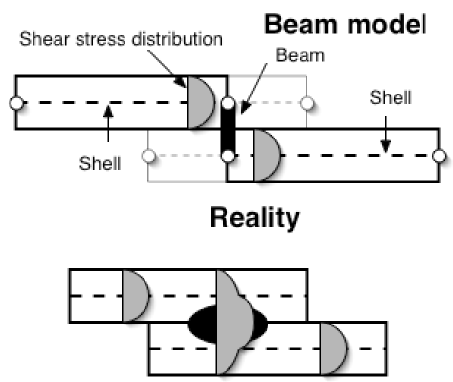

Figure 3. Through-thickness shear distribution in shells in beam RSW model.

It is important to point out that the maximum shear stress in the weld nugget could be the primary stress component causing the interfacial failure of RSW. For RSW in *conventional* steel structures, the dominant failure mode is the button pull-out and the inadequate calculation of the shear stress may not be a major concern in impact simulation of vehicles. On the other hand, for AHSS RSW, accurate determination of the shear stress may be critical because of the reported interfacial failure or mixed interfacial plus pull-out failure mode. The brittle fracture associated with the interfacial failure of the spot-weld is more likely during impact where plastic deformation of the base material may be constrained by large elastic stress field. Compared to a gradual increase in hardness in the HAZ in mild steel RSWs, the AHSS exhibit sharp hardness change [15] that adds to brittleness and notch sensitivity. In addition, the multiple failure modes and the changes in failure modes under different loading conditions require development of more versatile failure criteria based on the fracture and damage mechanics principles than the resultant force-based ones. From the structural stiffness perspective, the bar and beam models typically yield acceptable accuracy under tension, out-of-plane torsion and bending loads. However, the stiffness models are highly inaccurate for in-plane torsion and shear.

Approach and Work Scope

This program aims at (1) developing a new, robust spot-weld CAE simulation approach that provides the required accuracy of stress distribution to allow for realistic representation of different failure modes and failure mode transition as a function of impact, welding conditions and materials while maintaining the computational efficiency; and (2) a companion experimental database on the performance of RSW in AHSS components during impact. Three major research activities are planned to achieve the above program objectives.

- A new spot-weld-element formulation,
- A strain-rate-sensitive constitutive model incorporating the complex variations of microstructure and property in the RSW,
- Deformation and failure behavior database of AHSS spot-weld under different dynamic-loading conditions.

It is expected that the effort will be divided into two phases. The first phase will be an initial development of the SWE modeling framework and demonstration of the effectiveness of such modeling approach for the steel grades, thickness, and weld conditions selected by the Auto/Steel Partnership (A/SP). The initial development will cover two AHSS grades and one gauge thickness. The deliverables at the end of the first phase will be the initial version of the SWE and its implementation in FEM crash codes. The constitutive models to be used in a SWE will be based on strain-rate-sensitive elasto-plastic fracture and damage mechanics, and incorporate the microstructure changes in the weld region of AHSS. Welding process modeling and weld-microstructure characterization will be used to understand the welding effects. Failure criterion properly dealing with the failure mode changes during impact of AHSS spot-weld will be formulated based on the experimental data and fracture mechanics and damage mechanics principles. Figure 4. shows the organization and relationship among different tasks of the project.

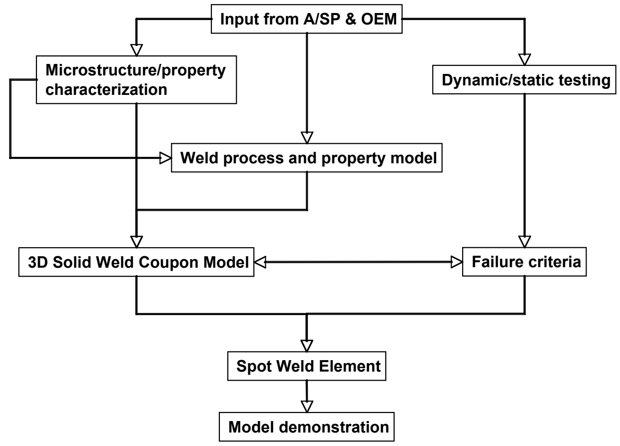

Figure 4. Project plan.

If the initial feasibility phase successfully demonstrates the effectiveness of the new modeling approach, a more comprehensive development phase will follow with the objectives of (1) further refining the SWE formulation and implementation procedure for different types of AHSS and component configurations, (2) more comprehensive component-level testing and model validation, and (3) expanding to other lightweight materials (Al, Mg alloys) and welding processes (weld bonding, friction-stir spot welding, etc).

Progress to Date

Working with the Strain Rate Characterization Committee of the Auto/Steel Partnership (A/SP, a test plan for producing welded coupons and dynamic testing has been finalized. Three steels have been selected: DQSK (IF) baseline mild steel, DP780, and boron steel. All steels sheets will be in the thickness range of 1.0 to 1.2-mm nominal. The dynamic testing will begin with lap-shear and cross-tension configuration. The mixed-loading-mode coupon and fixture design is underway and will be finalized before February 2007. Three different weld-nugget sizes will be made to study the transition of failure modes for each steel under different loading rate conditions. All welds will be made in 2-T stack-up configuration in this phase. The A/SP Strain Rate Characterization Committee will issue a procurement request to welding vendors to produce the welded coupons for dynamic testing using welding conditions similar to those used in the production environments. All welded coupons will be fabricated before February 2007.

In addition, we have completed a critical review on modeling the spot-welds in automotive crash simulations. The review focused on the current state-of-the-art modeling approaches and their respective characteristics. A letter report is under preparation to summarize the critical review.

Conclusions

This is a new program started in August 2006. Working with the Strain Rate Characterization Committee of A/SP, we have finalized the testing matrix for lap-shear and cross-tension dynamic testing and the specifications to produce the welded testing specimens. The program is on time and on budget.

Presentations/Publications/Patents

None in FY 2006.

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